CURRENT ELECTRICITY

Kirchhoff's Law [Gustav Robert Kirchhoff]

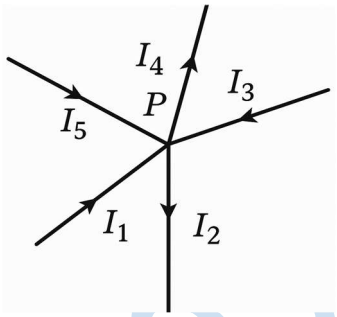
1. Kirchhoff's First Law: [Current Law or Junction Law] (In 1842)

Statement: The algebraic sum of electric current at any junction is always equal to zero. i.e. ΣI = 0

Sign Conventions: The current coming towards the junction is positive and the current leaving the junction is negative.

Example:

Consider a junction J in a circuit, where five conductors meet.



Applying Kirchhoff's first law,

$$I_1 - I_2 + I_3 - I_4 + I_5 = 0$$

$$\therefore I_1 + I_3 + I_5 = I_2 + I_4$$

Thus, the total coming towards the junction is equal to the total current leaving the junction. This is the principle of conservation of charge.

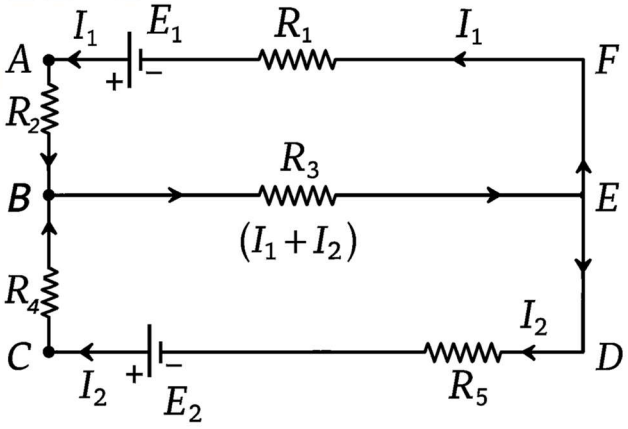
2. Kirchhoff's Second Law: [Voltage Law or Loop Theorem] : (In 1842)

Statement: In a closed loop of an electrical network, the algebraic sum of the potential differences for all components plus the algebraic sum of all E.M.F.s is equal to zero.

i.e. $\Sigma IR + \Sigma E = 0$

Sign Conventions:

1) While tracing the circuit, the potential difference (P.d.) across resistances taken in the direction of conventional current is negative (-ve), and the potential difference taken against the direction of conventional current is positive (+ve).
2) The E.M.F. is positive (+ve) if we traverse from the negative (-ve) terminal to the positive (+ve) terminal inside the cell. The e.m.f. is negative (-ve) if we traverse from the positive (+ve) terminal to the negative (-ve) terminal.



For loop ACDFA:

$$-I_1R_2 + I_2R_4 - E_2 + I_2R_5 - I_1R_1 + E_1 = 0$$

$$\therefore E_1 - E_2 - I_1(R_2 + R_1) + I_2(R_4 + R_5) = 0$$

Applying Kirchhoff's law,

For loop ABEFA:

$$-I_1R_2 - (I_1 + I_2)R_3 - I_1R_1 + E_1 = 0$$

$$\therefore E_1 - I_1(R_2 + R_1 + R_3) - I_2R_3 = 0$$

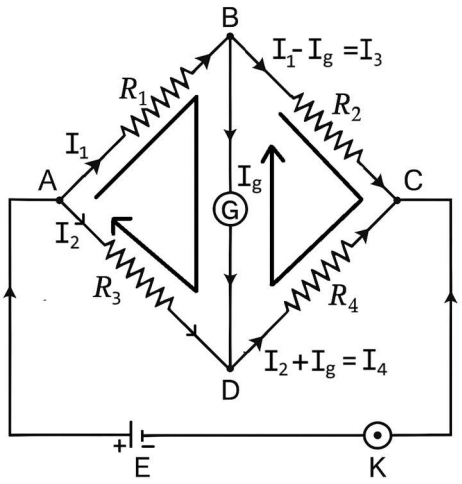
Applying Kirchhoff's law for the loop 'BCDEB'

$$I_2R_4 - E_2 + I_2R_5 + (I_1 + I_2)R_3 = 0$$

Kirchhoff's second law is in an accordance with **The Law of Conservation of Energy**.

Wheatstone's Network :

When four resistances R_1,R_2,R_3, & R_4 are connected to form a quadrilateral ABCD as shown in the figure, then such an electrical network is known as Wheatstone's Network or Wheatstone's bridge. In this case a cell is connected between point A & C, & the galvanometer is connected between the point B & D. Then the values of the resistances are adjusted so that, the current flowing through the galvanometer is zero (i.e. I_g= 0). Then the bridge is said to be balanced i.e. when the bridge is balanced then, Potential at B = Potential at D, i.e, $V_B = V_D$.



Condition for balanced bridge:

1) By using K.V.L.:

Applying K.V.L. to the loop ABDA

$$i_1R_1 + IgG - i_2R_3 = 0$$

But for balanced bridge, I_g = 0

$$i_1R_1 = i_2R_3 \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Applying K.V.L. to closed loop BCDB,

$$I_3R_2 - I_4R_4 - I_gG = 0$$

But $I_g = 0$

$$\therefore I_3R_2 = I_4R_4 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

But, $I_3 = I_1 - I_g$ & $I_4 = I_2 + I_g$

equation (2),

$$(I_1 - I_g)R_2 = (I_2 + I_g)R_4$$

$$I_1R_2 - I_gR_2 = I_2R_4 + I_gR_4$$

But, $I_g = 0$

$$\therefore I_1R_2 = I_2R_4 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Divide equation (2) & (3)

$$\therefore \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

This is required balanced condition.

2) By using Ohm's law:

Let, V_A, V_B , V_C & V_D be the potentials at points A, B, C & D resp.

When, $V_B = V_D$, then the bridge is said to be balanced.

By using Ohm's law,

$$\left.\begin{aligned} V_A - V_B\ (across\ R_1) &= I_1R_1 \\ V_B - V_C\ (across\ R_2) &= I_1R_2 \\ V_A - V_D\ (across\ R_3) &= I_2R_3 \\ V_D - V_C\ (across\ R_4) &= I_2R_4 \end{aligned}\right\} \ldots . Equation\ (3)$$

Putting the values from equation (3) into equations (1) and (2):

$$I_1R_1 = I_2R_3 \quad \ldots . (4)$$

$$I_1R_2 = I_2R_4 \quad \ldots . (5)$$

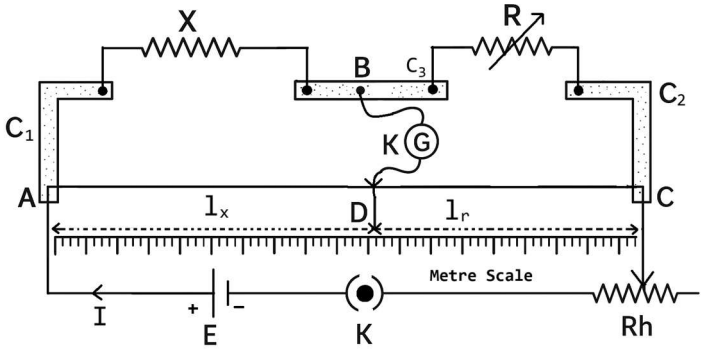
Divide equation (4) and (5):

$$\therefore \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

This is the required balanced condition.

Meter Bridge :-

It consists of three copper plates, which are fixed on a wooden board, so as to form two gaps. In first gap the unknown resistance X is connected & in second gap the resistance box(R.B.) is connected. At the junction of these two (B) one terminal of galvanometer is attached, while the other terminal is connected to jockey (J). A uniform conducting wire about 1 m in length having some resistance is stretched between the points A & C. (manganin wire). A cell, key and Rheostat are connected in series with the wire.



- **Procedure (Method):**

  Connections are made as shown in fig. above.

  Initially a suitable resistance is introduced in the circuit from the resistance box. Then by touching the jockey at different points on the wire and a point D is obtain such that for which the galvanometer shows no deflection. This point D is called Null point. After that the length AD & CD are measured,

$$\frac{X}{R} = \frac{Resistance\ in\ wire\ I_x}{Resistance\ in\ wire\ I_R}$$

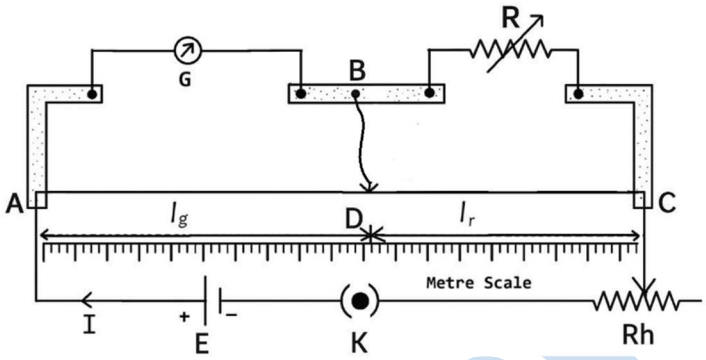
$$\frac{X}{R} = \frac{\sigma I_x}{\sigma I_R} \qquad \ldots . where\ \sigma\ the\ resistance\ per\ unit\ length$$

$$\frac{X}{R} = \frac{I_x}{I_R}$$

Educational Notes

Kelvin's Method to determine resistance of Galvanometer:

It consists of three copper plates, which are fixed on a wooden board, so as to form two gaps. In first gap a galvanometer whose resistance is to be determined is connected and in second gap resistance box is connected. At the junction of these two i.e. at point B, a jockey J is connected. A uniform conducting wire about 1 m in length, having some resistance is stretched between the points A & C. A cell, key & Rheostat are connected in series with the wire.



- **Procedure (Method):**
  Connections are made as shown in fig. above.
  Initially suitable resistance is introduced in the circuit from resistance box. Then the galvanometer shows some deflection. It is noted down. The jockey is touched at different points on the wire & a point D is obtain such that the galvanometer shows the same deflection, which was noted before. This point D is called equal deflection point. After that, the length AD & CD are measured, suppose these are I_G & I_R respectively.

$$\frac{G}{R} = \frac{Resistance\ in\ wire\ I_G}{Resistance\ in\ wire\ I_R}$$

$$\frac{G}{R} = \frac{\sigma I_G}{\sigma I_R} \qquad \ldots . where\ \sigma\ the\ resistance\ per\ unit\ length\ of\ wire$$

$$\frac{G}{R} = \frac{I_G}{I_R}$$

$$G = \left(\frac{I_G}{I_R}\right) R\ or\ G = \left(\frac{I_G}{100 - I_G}\right) R$$

By using this formula unknown resistance of galvanometer is determined.

Sources of error & their minimisation in meter-bridge :

1) Error due to non-uniformity of wire : If the wire is non-uniform, the resistance per unit length of the wire does not remains the same & the null point obtain would not be correct.
   To minimize this error wire used must be uniform i.e. of same cross-section.
2) Error due to Contact resistance :It affects the null point & introduces error in an unknown resistance. To minimize this unknown(X) and known resistance R are interchanged. The null point is found out again and X is calculated.
3) Error due to non-exact coincidence with zero & 100cm ark of scale : To minimize this error, null point is obtained near middle one third portion of the wire.
4) Error due to sliding of jockey on the wire : Due to sliding of the jockey, heat is produced due to friction. Thus, the area of wire can be deformed and resistance of the wire may change. To minimize this error, jockey is tapped on the wire.
5) Error due to heating effect of the cell current :Due to this resistance of wire increase. To minimize this error, circuit is switched off after every reading.

Potentiometer :

A Potentiometer is a device to measure unknown e.m.f. by comparing it with known e.m.f. in the electric circuit. Potentiometer consists of a thin uniform resistance wire about 1 to 10 meter long use as per convenience. This wire is made up of a material having low temp. coefficient. one end A of the wire is connected to the positive (+ve) terminal of battery & the other end to the negative (– ve) terminal of battery through key.

- **Principle of Potentiometer :**
  Statement : " For a steady current flowing through a potentiometer wire, the P.D. between any two points of the wire is directly proportional to the length of the wire between these two points ".

Educational Notes

Proof:

Let,

$V_{AB} \rightarrow P.D.\ between\ the\ points\ A\ \&\ B$

$V_{AP} \rightarrow P.D.\ between\ the\ points\ A\ \&\ P$

$\sigma \rightarrow Resistance\ per\ unit\ length\ of\ wire\ AB$

$R_{AB} = \sigma L \rightarrow Resistance\ of\ wire\ AB$

$R_{AP} = \sigma l \rightarrow Resistance\ of\ wire\ AP$

$\therefore$ By Ohm's law,

$V_{AB} = IR_{AB} = I\sigma L$

$\therefore I = \frac{V_{AB}}{\sigma L}$ ..... (1)

Also,

$V_{AP} = IR_{AP} = I\sigma l$

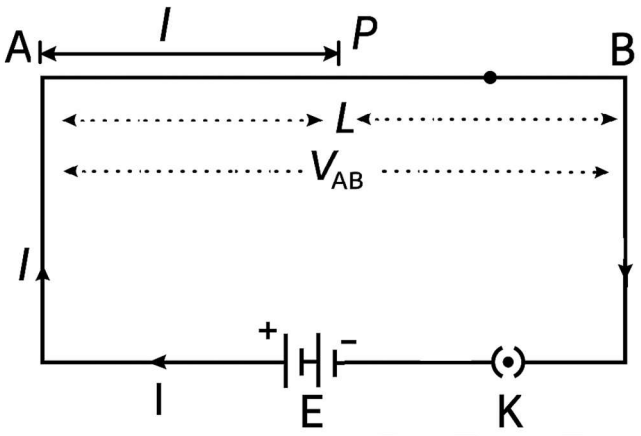
$I = \frac{V_{AB}}{\sigma L} \times \sigma l$

$V_{AP} = \left(\frac{V_{AB}}{L}\right) \times l$

$V_{AP} = \propto l \quad \ldots\ldots \therefore V_{AB}\ and\ L\ are\ constant$

$\therefore \quad \frac{V_{AP}}{t} = K = constant$

Where K is called Potential gradient of wire.



Use of Potentiometer to compare e.m.f. of two cells :

1. **$\frac{E_1}{E_2}$ by Direct method (Individual cell method) :-**

$E_1, E_2 \rightarrow E.M.Fs.\ of\ two\ cells\ resp.$

$K, K_1, K_2 \rightarrow Keys$

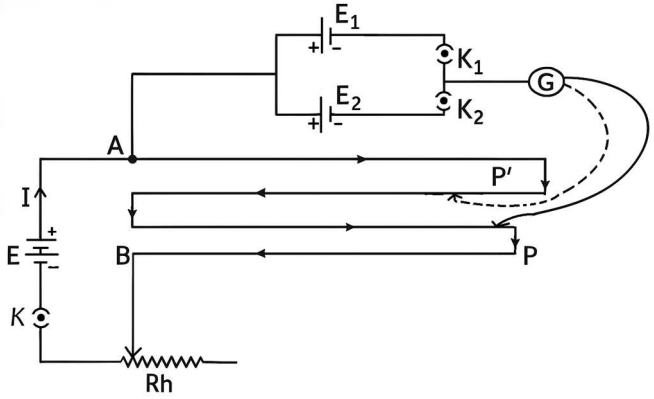
$J_1, J_2 \rightarrow Jockies$

$G \rightarrow Galvanometer$

Connections are made as shown in fig.

Initially the P.D. between the points A & B is measured, suppose it is V. then the potential gradient K is measured $\left(K = \frac{V}{L}\right)$. The emf of a battery is taken greater then E_1 & E_2.

Now close the keys K & K_1, so that the cell having emf E_1 is connected in the circuit. Then by touching the jockey J_1 at different point on wire, null point D_1 is obtained. Then balancing length AD_1 is measured, suppose it is l_1.



$E_1 = l_1 K$ .....(1)

Now key K_1 is opened and K_2 is closed, so that the cell having emf. E_2 is connected in the circuit. Then by similar procedure, the null point D_2 is obtained and balancing length l_2 is measured.

$E_2 = l_2 K$ .....(2)

Divide equation (1) by (2),

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

Thus e.m.f. of two cells can be compared with the help of potentiometer.

2. **$\frac{E_1}{E_2}$ by combination method i.e, Sum & diff. method :**

$E_1, E_2 \rightarrow E.M.Fs.\ of\ two\ cells\ resp.$

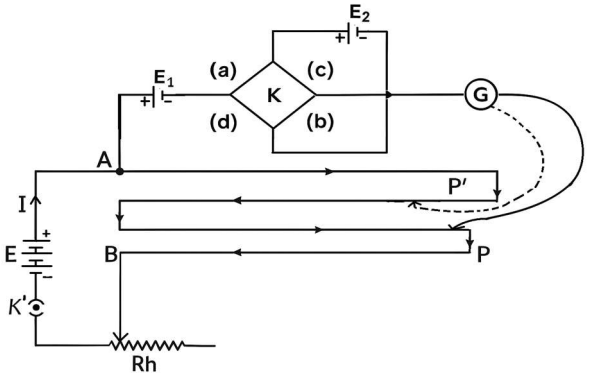
$J_1, J_2 \rightarrow Jockies$

$R \rightarrow Revelside\ key$

$K \rightarrow Key$

Connection are made as shown in fig.

Initially P.D. between the point A & B is measured, suppose it is V. Then the potential gradient K is



measured. After that the emf of a battery is taken greater than E_1+E_2.

Now close the key K and insert the plugs in position 1 & 2 of the reversing key, so that the emf becomes E_1+E_2. Then by touching the jockey J_1 at different points on the wire & null point D_1 is obtained. The balancing length l_1 is measured.

$E_1+E_2 = l_1K$ ……(1)

Now removing the plugs from position 1 & 2 and insert them in position 3 & 4 of reversing key, so that the emf becomes $E_1 - E_2$. Again the null point D_2 is obtained and the balancing length l_2 is measured.

$E_1-E_2 = l_2K$ ……(2)

Divide equation (1) by (2),

$$\frac{E_1 + E_2}{E_1 - E_2} = \frac{l_1 K}{l_2 K}$$

∴ on simplifying this equations we get, (By Componendo & Devidendo)

$$\frac{E_1}{E_2} = \frac{l_1 + l_2}{l_1 - l_2}$$

Thus, by knowing l_1 and l_2, emfs can be compared.

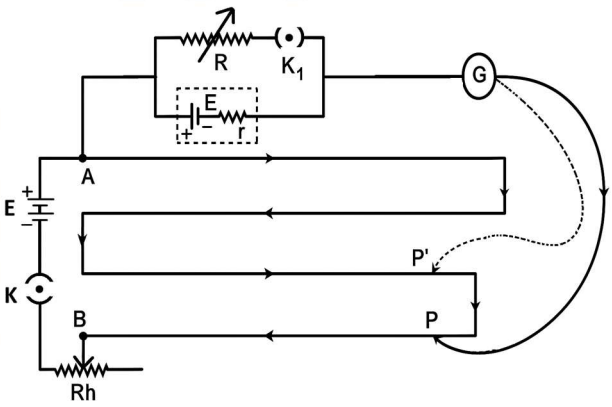
Determination of Internal resistance of a cell :

$E \rightarrow E.M.Fs.\ of\ cell$

$\rightarrow Resistance\ Box$

$K, K_1 \rightarrow Keys$

$J_1, J_2 \rightarrow Jockies$



Connections are made as shown in fig. above

Resistance box is not connected in the circuit. Then with the help of Jockey J_1 the null point D_1 is obtained and the corresponding balancing length l_1 is measured.

$E=l_1K$ ……(1)

where K is the potential gradient

Now close the Key K_1. So that the resistance box is connected in the circuit. Then introduce the suitable resistance from resistance box in the circuit and with the help of jockey J_2, null point D_2 is obtained. The corresponding balancing length l_2 is measured.

$\therefore\ P.D.across\ R\ =\ P.D.across\ l_2$

$V=l_2K$……(2)

Divide equation (1) by (2),

$\frac{E}{V} = \frac{l_1}{l_2}$ …… (3)

Let I is the current in a closed circuit formed by R, r & E.

Then by Ohm's law,

$E = I(R + r)$ ……(4)

The P.D. across R is given by,

V= IR ….. (5)

Divide equation (4) by (5)

$\frac{E}{V} = \frac{R+r}{R}$ ……(6)

compare equation (3) & (6)

$\frac{l_1}{l_2} = \frac{R+r}{R}$

$\frac{l_1}{l_2} = 1 + \frac{r}{R}$

$\frac{r}{R} = \frac{l_1}{l_2} - 1$

$r = \left(\frac{l_1}{l_2} - 1\right) R$

$r = \left(\frac{l_1 - l_2}{l_2}\right) R$

using this equation the internal resistance of a cell can be found.

Education Notes

Advantages of Potentiometer over Voltmeter :

1. A Potentiometer can be used for the measurement of very small P.D. accurately, whereas voltmeter cannot be used to measure small P.D. (It measure terminal P.D.).
2. The accuracy of potentiometer can be increased by increasing the length of wire, while accuracy of voltmeter cannot be increased.
3. By increasing length of potentiometer wire, its sensitivity can be increased so that it is more sensitive, whereas voltmeter is less sensitive.
4. The internal resistance of a cell can be measured with the help of potentiometer.

Disadvantages of Potentiometer :

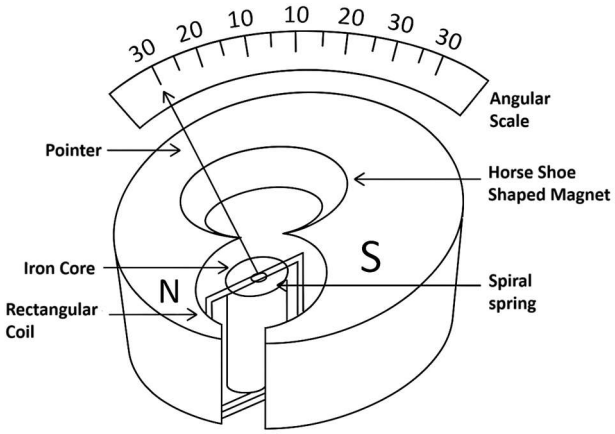
1. Voltmeter gives direct reading, but potentiometer is nct so.
2. Voltmeter is portable whereas a potentiometer is non-portable.

Distinguish between Potentiometer and Voltmeter :

Sr. No.	Potentiometer	Voltmeter
1.	It is used to measure the e.m.f. of cell and P.D.	It is used to measure only terminal P.D. of cell.
2.	It is used to measure internal resistance of cell.	It can be used to measure the internal resistance of the cell.
3.	It is most accurate.	It is less accurate.
4.	It does not give direct readings.	It gives direct readings.
5.	It is of large size.	It is of small size.
6.	It can be used to measure very small P.D.	It is used to measure large voltage.
7.	It works on null deflection method.	It works on deflection method.
8.	Its sensitivity is very high.	Its sensitivity is low.

Galvanometer:

A galvanometer is a device used to detect weak electric currents in a circuit. It has a cell pivoted (or suspended) between concave pole pieces of strong laminated horse shoe magnet. When electric current is passed through a coil, the coil is rotated (or deflects). The deflection of the coil is directly proportional to the current passing through the coil. The deflection of the coil can be read with a pointer attach to the coil, on a circular scale provided indicator the current through galvanometer or potential difference across it.



AMMETER: -

Explain how will you convert a M. C. G into an ammeter, derive the necessary formula? Or derive the necessary formula for shunt resistance required to convert a M. C. G into an ammeter. Explain why the ammeter must have low resistance?

Definition: - Where pivoted coil type M.C.G is design to measure the current in ampere it is known as ammeter.

When a M.C.G is connected in series with the circuit then the total resistance of circuit increases and due to this the current through the circuit decreases. Hence some errors are involved in the measurement of current. But the galvanometer shows large deflection for small current.

Education Notes

Therefore, large currents cannot be measured by it. Hence the resistance of small value is connected in parallel with a galvanometer. This low value resistance is known as shunt.

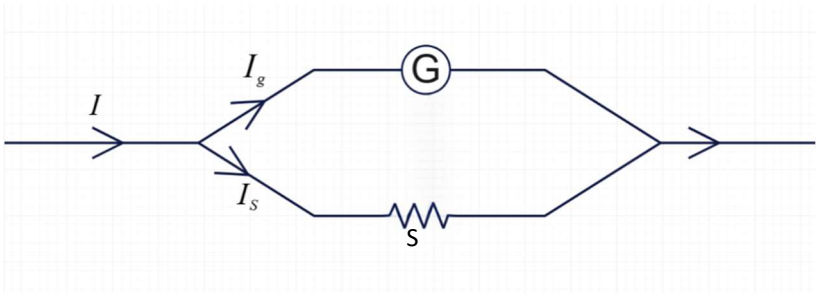
Functions of shunt: -

(1) It decreases the resistance of ammeter.

(2) It allows large amount of current flowing through it and thus helps the galvanometer to measure the large current without damaging it.

(3) By connecting the shunt of proper value, the range of ammeters can be changed.

Expression for shunt: -



Let, I = maximum current G = Resistance of galvanometer

S = shunt resistance I_g = current flowing through the galvanometer.

I_s = current flowing through the shunt

We have, At junction A, $I = I_g + I_s$

$I_s = I - I_g$ --------- (i)

As galvanometer and shunt are connected in parallel

P.D. across G = P.D across S

$I_g G = I_s S$ ---------- (ii)

$S = \frac{I_g G}{I_s}$

$S = \frac{I_g}{I - I_g}$ G ----------(iii)

By using this formula the required value of shunt can be determined

Remark :-

(1) From equation (iii)

$I S - I_g S = I_g G$

$I S = I_g G + I_g S$

$I S = (G + S) I_g$

$I_g = \frac{S}{S + G} I$

By using this formula the current flowing through galvanometer is determined.

(2) From equation (ii)

$(I - I_s) G = I_s S \quad ----[since\ I = I_g + I_s]$

$IG - I_s G = I_s S$

$IG = I_s S + I_s G$

$IG = I_s(S + G)$

$I_s = \frac{G}{S + G} I$

By using this formula the current flowing through the shunt is determined.

(3) As G & S are parallel, then the equivalent resistance (R) is.

$\frac{1}{R} = \frac{1}{G} + \frac{1}{S}$

Educational Ne

$$\frac{1}{R} = \frac{G+S}{SG}$$

$$R = \frac{SG}{G+S}$$

By using this formula equivalent resistance can be determined.

VOLTMETER :-

[Explain how will you convert a M. C. G. into a voltmeter. Derive the necessary formula . Or
Explain why it is necessary to convert a high value resistance in series with M. C. G to convert it into a voltmeter.]

Definition: - A device which measures the P.D. between any two points in the circuit, is known as voltmeter.

Requirements: -

1) Voltmeter should be sufficient sensitive.
2) Voltmeter should have high resistance.
3) It should have sufficient range.
4) It should give direct reading.

Voltmeter is a pivoted type M.C.G. with high resistance in series with it. This high resistance is called as multiplier.

Necessity of high resistance: -

1) As the resistance of galvanometer is low hence the P.D. between the Points is lowered. This lower value is measured by galvanometer. Seance, some errors are involved.
2) Galvanometer gives full scale deflection for a small P.D. Hence it will be damaged due to large P.D across it.

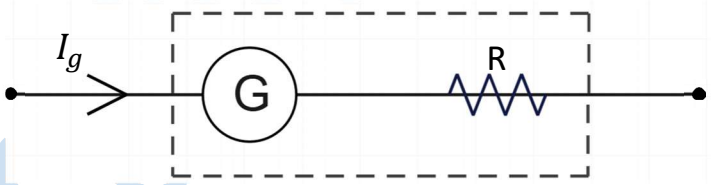
Thus, the resistance of voltmeter must be high.

Functions of resistance (multiplier): -

(1) It makes the total resistance between the terminals of instrument high. Hence, the original current in the circuit practically remains the same.

(2) It divides small and safe P.D. across the galvanometer and excess P.D. across itself.

Expression for high resistance: -



Let I_g = current flowing through voltmeter. R = Required value of series resistance.

V = P.D. across galvanometer and series resistance

By Ohm's law,

$V = I_g (G+R)$

$\frac{V}{I_g} = G + R$

$$R = \frac{V}{I_g} - G$$

By using this formula, the value of multiplier can be determined.

Educational Notes

Distinguish Between Ammeter & Voltmeter

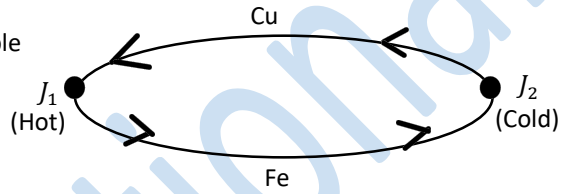
Sr. No.	AMMETER	VOLTMETER
1	M.C.G. can be converted into ammeter by connecting a low value resistance in parallel with galvanometer.	M.C.G. can be converted into ammeter by connecting a high value resistance in series with galvanometer.
2	The resistance of ammeter is very low.	The resistance of voltmeter is very high.
3	While measuring the current it is always connected in series with the circuit.	While measuring the P.D. it is always connected in parallel with the circuit.
4	To measure a large current a shunt (parallel) resistance is required.	To measure a larger P.D. a series resistance is required.
5	Value of shunt $S = \left[\frac{I_g}{I - I_g}\right] G.$	Value of high resistance $R = \frac{V}{I_g} - G.$
6	For ideal ammeter resistance is zero.	For an ideal voltmeter resistance is infinite.
7	Ammeter connected tin circuit to measure current in series.	Voltmeter connected in circuit to measure voltage in parallel.

Thermoelectricity: -

[$\boldsymbol{Ques.\ Define\ Thermocouple}$ & $\boldsymbol{What\ is\ Thermoelectricity}$]

• **Thermocouple: -** The Closed circuit of two dis-similar metallic core joined at their ends to form two junction is called Thermocouple.

Ex. Consider a Cu-Fe Thermocouple



When one junction of Thermocouple is kept hot (J_1) % other is cold (J_2), then a small emf is developed, which sends the current through it.

The emf so produced is called Thermo emf & the current is called Thermoelectric current.

• **Thermoelectricity: -**

Define: - The conversion of heat energy into electrical energy by using a Thermocouple is called Thermoelectricity.

• **Thermo emf (Thermoelectric emf): -**

Define: - The production of emf in a Thermocouple due to the temp. difference between. two junction is called Thermo emf

• **Thermoelectric current: -**

Define: - The production of current in a Thermocouple due to the temp. difference between two junction is called Thermoelectric current.

• **Seebeck effect :-**

[$\boldsymbol{Ques.\ State}$ & $\boldsymbol{explain\ Seebeck\ effect}$]

The phenomenon of producing thermoelectric emf. in a Thermocouple due to temp. difference between two junctions is called seekbeck effect.

Consider a Cu-Fe thermocouple with two junctions J_1 & J_2. A galvanometer is connected in thermocouple to detect the thermoelectric current.

When both the junctions of thermocouple are at the same temperature, the galvanometer shows no defection. It means that there is no thermoelectric current.

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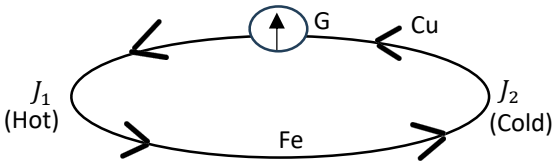
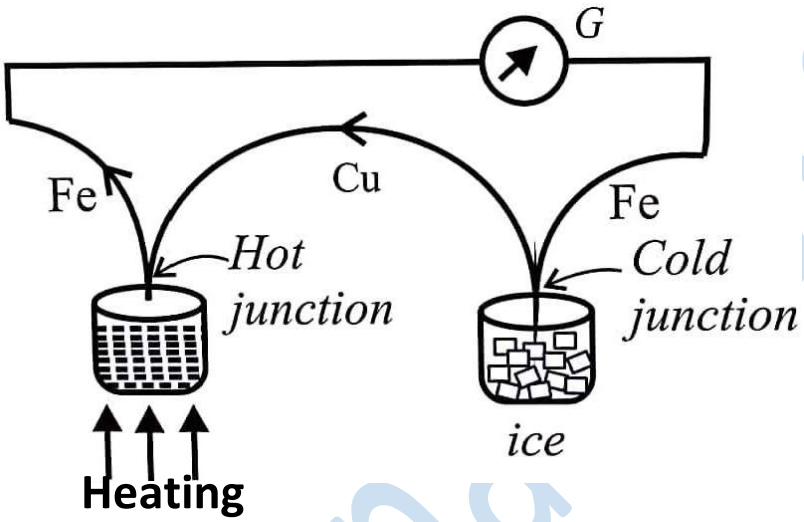
Now the junction J_1 is hot & junction J_2 is cold. Then it is observed that, galvanometer shows some deflection, because the thermoelectric current is produced in thermocouple.



The flow of thermoelectric current indicates that there is some source of emf in the circuit. This emf is called thermoelectric emf.

The hot & cold junctions are interchanged, then the direction of thermoelectric current is revered. Thus seebeck effect reversible effect.



Application of potentiometer: -

1) **Voltage Divider: -** The potentiometer can be used as a voltage divider to continuously change the output voltage of a voltage supply.

   In this case the voltage divides in proportion to the length of potentiometer wire.

2) **Audio Control: -** Sliding potentiometer are commonly used in Morden law-power audio systems as audio control drivers, both sliding and Rotatory potentiometer (Knobs) are regularly used for frequency attenuation, loudness control and for controlling different characteristics of audio signals.

3) **Potentiometer or a Sensor: -** If the slider part of potentiometer is connected to the moving part of a machine, it can work as a motion sensor. A small displacement of moving part causes changes in potential which further amplified using an Amplifier circuit. The potential difference is calibrated in terms of the displacement of the moving part.

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